International cooperation to promote technologies reducing greenhouse gas emissions

Michael Hoel* and Aart de Zeeuw†

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Abstract

In this paper we extend the theory on international environmental agreements by introducing the option that countries can adopt a breakthrough technology at a certain cost and can invest in (spillover) R&D to lower this cost of adoption. Three types of subgame perfect equilibria between a coalition of countries and the other countries as individual outsiders can be distinguished: one in which only the coalition invests and adopts the new technology, one in which only the coalition invests but all countries adopt the new technology, and one in which all countries invest and adopt the new technology. In this framework we investigate for different sizes of the coalition the resulting welfare and we investigate the stability of the coalition. In this way we can identify situations in which large stable coalitions can occur. The resulting picture proves to be less grim than in the standard theory on international environmental agreements.

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Very preliminary, not to be quoted!

*Department of Economics, University of Oslo, P.O. Box 1095, Blindern, N-0317 Oslo, Norway, e-mail: m.o.hoel@econ.uio.no

†Department of Economics and CentER, Tilburg University, P.O. Box 90153, 5000 LE Tilburg, the Netherlands and The Beijer Institute of Ecological Economics, The Royal Swedish Academy of Sciences, Stockholm, Sweden, e-mail: a.j.dezeeuw@uvt.nl

1 Introduction

The theoretical literature on International Environmental Agreements usually presents a rather grim conclusion: stable coalitions are large if there is not much to gain from cooperation, and are otherwise typically very small (Barrett (1994)). The stability concept is based on the idea of internal and external stability, meaning that an individual country neither has an incentive to leave nor to join the coalition (see also Hoel (1992), Carraro and Siniscalco(1993)). The result that the free-rider incentive dominates the incentive to internalize externalities among the coalition members is rather robust. This concept originates from cartel theory (d'Aspremont c.s. (1983)).

This result was challenged from different angles. Chander and Tulkens (1995), for example, use the γ-core concept from cooperative game theory to show that the grand coalition is stable in this sense. The idea is very similar to the idea of trigger strategies in repeated games where the threat of loosing cooperative benefits prevents countries to deviate from cooperative behaviour. The essential difference is the assumption on the behaviour of the other coalition members in case a country defects. In the stability concept above the rest of the coalition stays intact, whereas in the γ-core concept the original coalition falls apart in case a group of countries defects. Diamantoudi and Sartzetakis (2002) and Eyckmans (2003) apply the idea of farsightedness to show that a set of stable coalitions exists, among which large ones. This idea originates from Chwe (1994) and others and basically assumes that other coalition members defect as well but only up to a new stable coalition is reached. This threat proves to be sufficient to sustain large coalitions, although in a dynamic context where detection of deviations takes time, this idea may not work either (de Zeeuw (2007)). In this paper we base ourselves on the concept of internal and external stability because the assumption seems reasonable for the current practice of international environmental agreements.

In a recent paper Barrett (2006) introduces the option of adopting "breakthrough" technologies, besides the standard marginal abatement options. This may be an important issue, especially for the possible successors of the Kyoto Protocol, because of the debate whether the treaty should focus on emission reductions in general or on technological change and because the CO_2 problem may require completely different technologies. If adoption costs are higher than the benefits, if only one country adopts, but lower than the benefits, if all countries adopt, a coalition is needed to get adoption of the technology by the coalition members. However, the stability requirement will lead to the smallest coalition that is profitable in this respect. Barrett (2006) continues by showing that if the technology exhibits increasing returns to adoption, full participation may be sustained. Barrett (2006) introduces R&D expenditures that are needed to make the new technology available at the fixed adoption costs. In this paper we make the adoption costs a function of R&D expenditures and focus on the R&D decisions. We abstract from the standard abatement options because the results are essentially the same if we include these options. We start with the case in which only the coalition invests in R&D. We show that it is possible that the coalition invests so much in R&D that all countries will adopt the new technology. This can happen because R&D expenditures that give minimal total costs for the coalition lead to sufficiently low adoption costs, but also because the coalition strategically increases R&D expenditures in order to induce the outsiders to adopt the new technology. However, stability considerations drive down the size of the coalition which either leads to a small coalition with adoption costs that are too high for the outsiders to switch to the new technology or to a situation where all countries adopt but the coalition bears all the R&D costs. If we introduce the option that outsiders invest in R&D as well, the picture changes. In principle it is possible now that the coalition fully exploits its Stackelberg power and invests nothing or very little in R&D. We restrict the outcomes, however, by the assumption that the coalition invests as least as much R&D to adopt the new technology itself, if that is profitable in the first place. We show that if the coalition still has some Stackelberg power left, it can induce the outsiders to bear a substantial part of the R&D costs. Stability considerations now drive up the size of the coalition which either leads to a situation where all countries adopt and almost evenly share the R&D costs or to a situation that is even closer to the social optimum. Note that full adoption may not be sufficient for the social optimum: it may still be beneficial to spend more R&D to lower the adoption costs.

The last part of the paper is very preliminary. Further research is needed to clarify and discuss all the possible outcomes in this case.

2 Development and adoption costs

We consider an economy with N identical countries that all have greenhouse gas emissions in the absence of any abatement efforts. We ignore all "traditional" abatement possibilities, and focus instead on the possibility of developing a new technology that will reduce greenhouse gas emissions in the countries adopting the technology. It is not difficult to show, however, that if we leave the traditional abatement possibilities open, the mechanisms that we develop in this paper still hold. For each country, the cost of adopting the new technology is c (which we below make endogenous), and if this technology is adopted the country's emissions are reduced by a fixed amount. The value of such a reduction is by choice of the monetary unit equal to 1 for each country. Clearly, once the technology is developed, it is individually rational for each country to adopt it if and only if $c \leq 1$. For the group of countries as a whole it is optimal to adopt the new technology if and only if $c \leq N$.

For countries to be able to adopt the new technology, it must first be developed. Such development requires R&D expenditures, and we assume that these expenditures give rise to a common knowledge pool that may make the new technology available and also affect the adoption costs. This is a similar assumption as in Barrett (2006). He assumes that if the sum of R&D expenditures in all countries, henceforth denoted M, is below some threshold, the new technology, that he calls a "breakthrough" technology, will not be available at any cost. If on the other hand M is at least equal to this threshold value, the technology will be available at some fixed cost c. An obvious generalization of this assumption is to assume that c is a declining function of M, $c = c(M)$. More precisely, we assume $c = c(M)$ with $c' < 0, c'' > 0$. If $c(M) > 1$ for all values of M (as is assumed by Barrett, 2006) it will never be individually rational for a country to adopt the new technology. We include this as a special case, but our main focus will be on the more interesting case in which $c(M) < 1$ for M sufficiently large. We assume throughout that $c(M) + M > 1$ for all M, so that it cannot be optimal for an individual country to develop and adopt the new technology unilaterally. Finally, we assume that for values of M giving $c(M) \leq 1$, $c(M)+M$ is increasing in M, i.e. $-c' < 1$. This last assumption is reasonable: If the opposite were true, one dollar of investment in this type of R&D would reduce the adoption costs for this technology by more than one dollar *for all countries.*

3 The social optimum and non-cooperative equilibria

In the social optimum either the technology is not developed or, more interestingly, developed and adopted by all countries. In the latter case the payoff to each country is

$$V(N) = N - \min_{M} \left[c(M) + \frac{M}{N} \right] \tag{1}$$

The optimal value of M is increasing in N, and we denote it by $M^*(N)$. If and only if $V(N) \geq 0$, it is socially optimal to develop and adopt the new technology. We assume henceforth that this inequality is satisfied.

Consider next non-cooperative equilibria of the two-stage game in which all countries first (stage one) decide how much to spend on R&D (if anything) and then (stage two) whether or not to adopt the new technology. Clearly, one sub-game perfect equilibrium is for no country to invest in developing the new technology (and thus also not adopting).

There may be a second equilibrium if $c(M) = 1$ for a sufficiently large value of M. Assume this is the case and denote this value of M by $\bar{M}$. A possible equilibrium is for all countries to invest $\bar{M}/N$ in the first stage and to adopt the technology in the second stage. Since by definition $c(\bar{M}) = 1$, this will give each country a net benefit equal to $N - 1 - \frac{\bar{M}}{N}$. This net benefit is non-negative if and only if

$$\bar{M} \leq N(N-1) \tag{2}$$

If this inequality holds, i.e. if net benefit is non-negative, no country will benefit by unilaterally deviating: by not adopting in the second stage a country gets the same payoff (benefits and adoption costs both go down by 1), while contributing less than $\bar{M}/N$ in the first stage will imply that no country adopts in the second stage, which will reduce the deviating country's payoff to zero (if the deviating country's R&D is zero in the first stage).

There may obviously also be non-symmetric equilibria of a similar type as above. However, there will be no equilibria with $M > \bar{M}$. The reason for this is our assumption that $c(M) + M$ is increasing in M, so that in a potential equilibrium with $M > \bar{M}$, an individual country can reduce its costs without affecting its benefits by reducing it R&D expenditures.

4 Equilibrium with a coalition and outsiders

Assume now that we have a coalition of size k, where $0 < k < N$. For now we take k as exogenous; this will be relaxed in the next section. This coalition plays a two-stage game with the $N-k$ remaining countries, henceforth called outsiders. In the first stage the coalition decides how much to spend on R&D, while each outsider is for now assumed to have no R&D. An interpretation of this could be that in order for R&D expenditures to have any effect, they must be coordinated, and therefore take place by the coalition. In section 6 we shall however consider the case in which outsiders also may invest in R&D.

In the second stage of the game, all players choose whether or not to adopt the new technology. At this stage, each outsider adopts if and only if $c(M) \leq 1$, and each of the coalition countries adopts if and only if $c(M) \leq k$ (since k is the benefit to each of the coalition countries if they all adopt). For the first stage of the game, the two interesting cases are thus $M < \bar{M}$ and $M \geq \bar{M}$.

If $M < \bar{M}$ in the equilibrium, the payoff to each of the coalition members is

$$\phi(k) = k - \min_{M} \left[c(M) + \frac{M}{k} \right] \tag{3}$$

since the benefit of emission reduction by the coalition countries is k for each coalition country. The solution to the minimization problem in (3) is denoted by $M^*(k)$ and satisfies

$$-c'(M^*) = \frac{1}{k} \tag{4}$$

Since $c'' > 0$, it is clear that M^* is increasing in k. The payoff above is only relevant if $M^*(k) < \bar{M}$. Note that in this case the decision of whether or not to be in the coalition must be binding. Otherwise, if there was a new choice to be in or out of a coalition of size k after the R&D investments are made, a single country would prefer to be outside a coalition of size $k-1$, since the adoption costs are larger than 1 in this case.

The equilibrium in which $M \geq \bar{M}$ is slightly more complicated. Consider the function

$$\Phi(k) = N - \min_{M} \left[c(M) + \frac{M}{k} \right] \tag{5}$$

which lies above $\phi(k)$ for $k < N$. If $M^*(k) \geq \bar{M}$ it is clear that $\Phi(k)$ is the payoff to each coalition country, since in this case all countries adopt the technology once it is developed, so that the benefit of reduced emissions is N for each coalition country. If $M^*(k) < \bar{M}$, the coalition may nevertheless choose $\bar{M}$ instead of $M^*(k)$ even if this gives the coalition higher total costs. The reason for this is that by choosing $\bar{M}$ instead of $M^*(k)$ it induces the outsiders to adopt the new technology, raising the benefits to each coalition country of reduced emissions from k to N. It is useful to consider the function (remembering that $c(\bar{M}) = 1$)

$$\bar{\Phi}(k) = N - \left[1 + \frac{\bar{M}}{k}\right] \tag{6}$$

Defining $\bar{k}$ as the value of k giving $M^*(k) = \bar{M}$, it is clear that[1]

$$\begin{aligned} \bar{\Phi}(\bar{k}) &= \Phi(\bar{k}) \\ \bar{\Phi}(\bar{k}) &< \Phi(k) \text{ for } k \neq \bar{k} \end{aligned}$$

Denote the value of k giving $\bar{\Phi}(k) = \phi(k)$ by k'. It is clear from the reasoning above that the actual payoff $V(k)$ to the coalition is defined by

$$V(k) = \left\{ \begin{array}{c} \phi(k) \text{ for } k \leq k' \\ \bar{\Phi}(k) \text{ for } k' < k \leq \bar{k} \\ \Phi(k) \text{ for } k > \bar{k} \end{array} \right\} \tag{7}$$

The three functions $\phi(k)$, $\Phi(k)$ and $\bar{\Phi}(k)$ are illustrated in Figure 1. The actual payoff $V(k)$ to the coalition is illustrated in this figure as the heavily drawn combination of the three original curves, and the value of k making $V(k) = 0$ is denoted k^0.

[Insert Figure 1 and Figure 2 here]

Figure 2 characterizes how the R&D expenditure of the coalition depends on its size, with the actual choice of M as the heavily drawn curve. For $k < k^0$ there is no R&D, for $k^0 < k < k'$ R&D expenditure is $M^*(k) < \bar{M}$, for $k' < k < \bar{k}$ R&D expenditure is $\bar{M}$, and for $k > \bar{k}$ R&D expenditure is

[1] Although only integers are relevant, it is useful to charachterize the properties of the payoff function for all real values of k.

$M^*(k) > \bar{M}$. We have drawn the figure so that all of these four regions exists, which need not generally be the case. For instance, we could have $k' < k^0$, in which case we either have no R&D or $M \geq \bar{M}$, implying that either no country or all countries adopt the technology. We could also have $\bar{k} > N$, implying that R&D will not exceed $\bar{M}$ no matter how large the coalition is. Finally, a possible outcome is that $k' > N$, so that R&D will be smaller than $\bar{M}$ and the outsiders will not adopt the technology no matter how large the coalition is.

5 Stable coalitions

So far, we have analyzed coalitions of arbitrary size. We now ask the question which coalition sizes are stable. We define stability as in Hoel (1992), Carraro and Siniscalco (1993) and Barrett (1994). In particular, prior to the two stage game considered so far, there is a "stage zero" in which each country chooses to join the coalition or not to join. In a subgame perfect equilibrium no country regrets it choice of being in or out of the coalition. For this to be the case, the equilibrium payoff to a coalition country in a coalition of size k must be at least as large as the equilibrium payoff to an outsider of a coalition of size $k-1$ (internal stability), and the equilibrium payoff to an outsider of a coalition of size k must be at least as large as the equilibrium payoff to a coalition country in a coalition of size $k+1$ (external stability). We can identify the stable coalitions by checking internal stability for each coalition size k.

The smallest interesting coalition is the one of size K^0 defined as the smallest integer that is at least as high as k^0. The payoff to each member of such a coalition is $V(K^0)$, which is nonnegative but small. This is a stable coalition: if one country instead of joining the coalition chooses to be an outsider, the coalition of size $K^0 - 1$ will not develop the new technology, so all countries in this case will get a payoff of zero. Since $V(K^0) \geq 0$ (and strictly positive unless k^0 is an integer), no potential member of the coalition of size K^0 can do better by being an outsider.

Consider next a coalition of size K satisfying $k^0 + 1 \leq K \leq k'$. The payoff to each member of such a coalition is $\phi(K)$,which is smaller than $K-1$ since $c(M) > 1$ in this case (see (3)). This coalition is not stable: if one country instead of joining the coalition chooses to be an outsider, the coalition of size

$K-1$ will develop and adopt the new technology, so the outsider will get a benefit of $K-1$ and have no costs. A potential member of the coalition of size K can thus do better by being an outsider.

Consider next a coalition of size K' defined as the smallest integer that is at least as high as $k^{'}$. The payoff to each member of such a coalition is $\bar{\Phi}(K') = N - \left[1 + \frac{\bar{M}}{K'}\right]$, while the payoff to an outsider of a coalition of size $K'-1$ is $K'-1$. For the coalition of size K' to be stable we must have

$$N - 1 - \frac{\bar{M}}{K'} \geq K' - 1 \tag{8}$$

If this condition holds, the coalition of size K' is stable, since no potential member of the coalition of size K' can do better by being an outsider.

We know from the definition of K' that

$$N - 1 - \frac{\bar{M}}{K'-1} < V(K'-1) = K' - 1 - \min_{M}\left[c(M) + \frac{M}{K'-1}\right]$$

A necessary condition for (8) to hold is therefore that

$$\frac{\bar{M}}{K'-1} - \frac{\bar{M}}{K'} > \min_{M}\left[c(M) + \frac{M}{K'-1}\right]$$

It seems quite implausible that this inequality will hold, unless K' is very small.

Consider next a coalition of size K satisfying $k'+1 \leq K \leq \bar{k}$. The payoff to each member of such a coalition is $\bar{\Phi}(K) = N - \left[1 + \frac{\bar{M}}{K}\right]$. An outsider of a coalition of size $K-1$ gets the same benefits and same adoption costs as members of a coalition of size K, but has no development costs. A potential member of the coalition of size K can thus do better by being an outsider, and therefore a coalition of size K satisfying $k'+1 \leq K \leq \bar{k}$ is not stable.

Finally, consider a coalition of size $K > \bar{k}$. The payoff to a coalition of size K is

$$N - c(M^*(K)) - \frac{M^*(K)}{K}$$

while the payoff to an outsider of a coalition of size $K-1$ is[2]

[2] If $K < \bar{k}+1$, $M^*(K-1)$ should be replaced by $\bar{M}$ in the formula below.

$$N - c(M^*(K-1)$$

The condition for stability is thus

$$N - c(M^*(K)) - \frac{M^*(K)}{K} \geq N - c(M^*(K-1)$$

or

$$c(M^*(K-1)) - c(M^*(K)) \geq \frac{M^*(K)}{K} \tag{9}$$

For this inequality to hold, adoption costs must decline quite significantly if the coalition is enlarged by one member. From (4) and the convexity of c we know that the l.h.s. of (9) cannot exceed $\frac{1}{K-1}[M^*(K) - M^*(K-1)]$, a necessary condition for (9) to hold is therefore that

$$\frac{M^*(K) - M^*(K-1)}{M^*(K)} \geq \frac{K-1}{K}$$

If for instance $K = 10$, the decline in R&D investment when the coalition size drops from 10 to 9 must be at least 90%. Although such cases cannot theoretically be ruled out, we find them quite implausible.

To summarize: we certainly have a stable coalition of size K^0 as defined above. From the discussion above it seems unlikely that there are any larger stable coalitions. There are two possible candidates for larger coalitions. One candidate is a coalition of size K' as defined above. An even larger stable coalition exists if there exists an integer K larger than $\bar{k}$ satisfying (9). However, none of them seems likely to occur.

6 Outsiders invest in development as well

Assume now that the outsiders spend R&D as well, in reaction to the R&D expenditures of a coalition of size k. Since $c(M) + M$ is increasing in M, it only makes sense for the outsiders to spend R&D if the coalition does not invest enough in R&D to lower the adoption costs to 1, i.e. if $M^k < \bar{M}$, where M^k denotes the R&D expenditures of a coalition of size k. Moreover, for the same reason, in equilibrium the outsiders will not spend more R&D than to make up for the difference between M^k and $\bar{M}$. This type of equilibrium is therefore characterized by a coalition of size k investing $M^k < \bar{M}$ and each of the $N-k$ outsiders investing $\frac{\bar{M}-M^k}{N-k}$.

Assume that total R&D expenditures are still larger than $M^*(k)$ if one of the outsiders deviates, i.e. assume that

$$M^k + (N-k-1)\left[\frac{\bar{M}-M^k}{N-k}\right] \geq M^*(k) \tag{10}$$

or

$$M^k \geq \bar{M} - (N-k)(\bar{M} - M^*(k)) \tag{11}$$

If one of the outsiders does not spend R&D, so that total R&D expenditures is smaller than $\bar{M}$ but still larger than $M^*(k)$, the payoff to outsiders is equal to k and therefore in this type of equilibrium outsiders only invest in R&D if

$$N - \left[1 + \frac{\bar{M}-M^k}{N-k}\right] \geq k \tag{12}$$

which also gives a lower limit for M^k. As Stackelberg leader in the R&D game, the coalition can hold the payoff of each outsider down to k by choosing

$$M^k = \bar{M} - (N-1-k)(N-k) \tag{13}$$

provided that this M^k satisfies condition (11). Two things are important to note here. First, if this M^k does not satisfy condition (11), the coalition can choose R&D expenditures equal to the r.h.s. of (11) so that the coalition will still adopt the new technology if the outsiders do not cover the difference with $\bar{M}$. Since coalition members invest more and outsiders invest less in this case, in equilibrium the payoff to coalition members is lower and the payoff to outsiders is higher. This is left for further research. Secondly, a more agressive approach of the coalition would be to spend nothing or very little on R&D and have the outsiders spend most of the R&D, but this would run the risk of ending up without adopting the new technology themselves while it would be favorable to do so. This is also left for further research.

The payoff $\Phi^*(k)$ to a coalition member becomes

$$\Phi^*(k) = \frac{N^2 - N - Nk + k^2 - \bar{M}}{k} \tag{14}$$

This result can also be found by substracting the total payoff to the outsiders $(N-k)k$ from the total payoff to all countries together $N(N-1) - \bar{M}$ and dividing this over the k coalition members. When we compare this to the case in section 4, where outsiders are not investing in R&D, it is interesting to note that in this case the payoff to a coalition member is substantially higher, at least up to coalition size $\bar{k}$, since

$$\Phi^*(k) - \bar{\Phi}(k) = \frac{(N-1-k)(N-k)}{k} \tag{15}$$

where $\bar{\Phi}(k)$ is given by (6) and is represented by the middle part of $V(k)$ in Figure 1. The reason the coalition can do better is this part is that the coalition can save on R&D costs by creating an incentive for outsiders to take part in R&D up to a total level of expenditures $(N-1-k)(N-k)$. Note that the difference between $\Phi^*(k)$ and $\bar{\Phi}(k)$, given by (15), is 0 for $k = N-1$ and for $k = N$. Therefore if $\bar{k} < N-1$ in Figure 1, $V(k) > \Phi^*(k)$ for $k > k''$, where k'' is the intersection point of $V(k)$ and $\Phi^*(k)$. This means that a coalition of size k, with $k'' < k \leq N$, can do better by switching to the equilibrium of section 4 and investing $M^*(k) > \bar{M}$ in R&D, which implies that the outsiders will not invest anything.

The next question is which coalition sizes are stable for this type of equilibrium. In such a Stackelberg game where lower R&D expenditures by the coalition are fully compensated by R&D expenditures by the outsiders, it can be expected that the size of the stable coalition may be high (see Finus (2003)). For internal stability we have to check

$$\frac{N^2 - N - Nk + k^2 - \bar{M}}{k} \geq k - 1 \tag{16}$$

and for external stability we have to check

$$k \geq \frac{N^2 - N - N(k+1) + (k+1)^2 - \bar{M}}{k+1} \tag{17}$$

It follows from (16) and (17) that the stable coalition size K^* has to satisfy

$$N - 1 - \frac{\bar{M}}{N-1} \leq K^s \leq N - \frac{\bar{M}}{N-1} \tag{18}$$

and is therefore equal to the largest integer at or below $N - \frac{\bar{M}}{N-1}$. Note that when N gets larger, K^s gets closer to N. The characteristics of this equilibrium are that the R&D expenditures of all countries together are equal to $\bar{M}$ and all countries adopt the new technology. A coalition of size k can hold the payoff of each outsider down to k, if condition (11) holds, so that the requirement of external stability drives the size of the coalition up as long as (17) is not satisfied. Without other considerations, the stable coalition size K^s is given by (18).

The question is how this equilibrium relates to the equilibria in section 4, represented in Figure 1. If $k < k''$, where k'' is the intersection point of $V(k)$ and $\Phi^*(k)$, the coalition will choose the equilibrium of section 6. Furthermore, if the largest integer below k'' is not larger than K^s, the requirement of external stability will drive the size of the coalition at least up to this point. For the smallest integer K^* above k'' the coalition will switch to the equilibrium of section 4 with $M^*(k) > \bar{M}$. We have already seen in section 5 that larger coaltions than K^* are generally not internally stable. However, because $V(K^*) > \Phi^*(K^*)$, by construction, and

$$\Phi^*(K^*) \geq K^* - 1 \tag{19}$$

if $K^* \leq K^s$, the coalition of size K^* is stable in this case.

To summarize: the usual grim picture in sections 4 and 5, where the size of the stable coalition is small and little in achieved in terms of emission reductions, substantially changes by introducing the option that outsiders invest in R&D as well. A numerical example may clarify part of this.

7 A numerical example

Assume that the function for adoption costs is given by

$$c(M) = \frac{\gamma}{M} \tag{20}$$

It follows that $\bar{M} = \gamma$ and with (4) that

$$M^*(k) = \sqrt{\gamma k} \tag{21}$$

so that $\bar{k} = \gamma$. Furthermore, it follows with (3), (6) and (5) that

$$\phi(k) = k - 2\sqrt{\frac{\gamma}{k}} \tag{22}$$

$$\bar{\Phi}(k) = N - 1 - \frac{\gamma}{k} \tag{23}$$

$$\Phi(k) = N - 2\sqrt{\frac{\gamma}{k}} \tag{24}$$

$$\Phi^*(k) = \frac{N^2 - N - Nk + k^2 - \gamma}{k} \tag{25}$$

Assume $N = 13$ and $\gamma = 16$. In this case $k^0 = 4$ and $\bar{k} = 16$. Only part of Figure 1 applies because $\bar{k}$ lies to the right of N and also k' does not exist, since $\bar{\Phi}(k^0) > 0$. Moreover, $\bar{\Phi}(k) = 0$ for $k = 1.33$ so that $k = 2$ is the stable coalition size for the equilibria of section 4 where only the coalition invests in R&D. In this case the two coalition members each spend 8 on R&D but still have a positive payoff because all countries will adopt, so that the coalition members end up with a payoff equal to 4. The other countries all end up with a payoff equal to 12. The average payoff is equal to 10.77.

However, if outsiders invest in R&D as well, the picture changes. Note first that in this case M^k, given by (13), satisfies (11) for all k. The requirement of external stability drives the size of the coalition up to the full coalition of size 13, where each country spends 1.23 on R&D and has a payoff equal to 10.77. Note that if a coalition of size 12 would form, each member of the coalition would spend 1.167 on R&D and have a payoff equal to 10.833 and the only outsider would spend 2 on R&D and have a payoff equal to 10. The average payoff does not change, but the division of the R&D expenditures and therefore the division of the payoffs over the countries becomes more even.

8 Conclusion

In order to solve the problem of greenhouse gas emissions, that may lead to climate change, countries can invest in R&D to lower the adoption costs of new technologies that substantially reduce or even eradicate greenhouse gas emissions. If it is not beneficial for an individual country to invest and adopt, an international environmental agreement is needed. This paper shows that if only the coalition invests in R&D, full adoption may result for certain coaltion sizes but these sizes are usually not stable, or it leads to a situation where the coalition bears all the R&D costs. However, if outsiders invest in R&D as well, large coalitions with full adoption and all countries sharing R&D costs may result.

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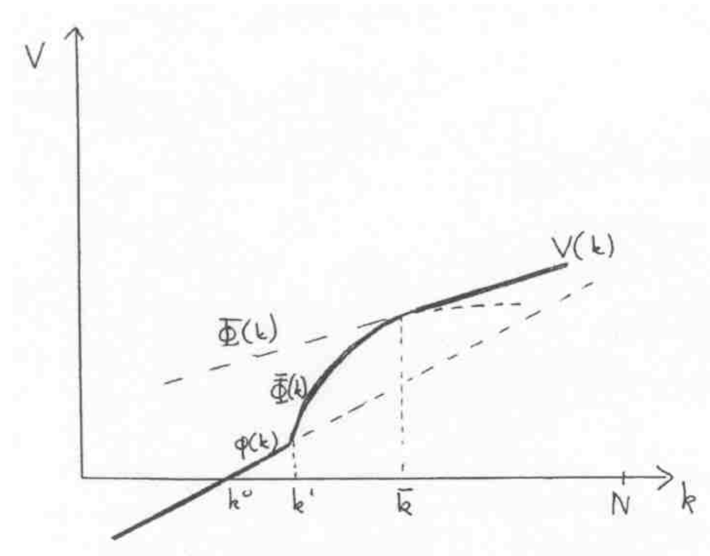

Figure 1: payoff member coalition of size k

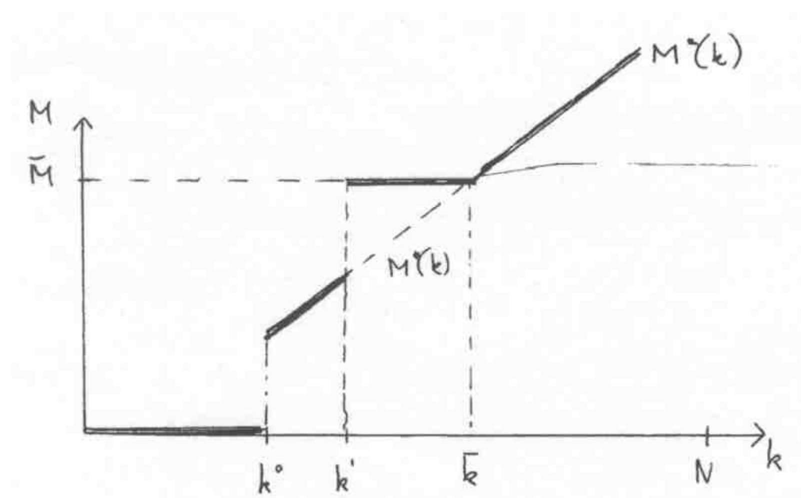

Figure 2: R&D expenditures coalition of size k